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MONOLITHIC MULTIAxis INTERFEROMETER

FIELD OF INVENTION

This invention relates to distance-measuring equipment, and in particular, to interferometers.

RELATED APPLICATIONS

5 This application claims the benefit of the priority date of U.S. provisional application 60/227,901 filed on August 25, 2000, the contents of which are herein incorporated by reference.

BACKGROUND

In the fabrication of an integrated circuit, there are steps during which a wafer rests on a moveable stage under a projector. As the stage moves, it experiences linear translation in a direction parallel to one of two coordinate axes that define the plane of the wafer. In addition, the stage experiences rotation about any of the three coordinate axes. During these steps, it is desirable to know, with great precision, the position and orientation of the moveable stage relative to the projector.

One approach to determining the motion of the stage is to use an interferometer to determine the distance to a measurement spot along the edge of the stage. This, however, only provides the extent to which the stage has translated along one of the coordinate axes. It does not provide information on the rotation of the stage about the three coordinate axes.

To obtain information about both the rotation and the translation of the stage, it is known to use three interferometers to measure the distance to three different reference spots that define a triangle on the edge of the stage. From these three distance measurements, one can infer the extent and direction of rotation experienced by the stage. For example, if a first reference spot is found to have moved closer to the interferometer and a second reference spot immediately below the first spot is found to have moved further from the interferometer, one can infer that the plate has rotated about a line joining the first and second reference spots. From the relative positions and distances to the first and second reference spots, one can calculate the extent of this rotation.

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It is also known to integrate the three separate interferometers into a single “multi-axis” interferometer, in which a single laser beam is split into three beams (one for each axis) by a beam multiplexer. These beams are directed to separate assemblies that typically include a polarizing beam splitter cube, a plane mirror, a corner cube retro-reflector, quarter-wave retarders, and mixing polarizers, all of which are oriented and configured to form reference beams and measurement beams for each interferometer axis. Assemblies of this type are described in U.S. Patent 4,802,764 to *Young* et al. and U.S. Patent 4,883,357 to *Zanoni*, et al., the contents of which are herein incorporated by reference.

The optical elements for directing the various beams in a multi-axis interferometer must be precisely aligned with each other for the multi-axis interferometer to provide accurate measurements. This alignment process is carried out at the time of installation and periodically thereafter, as the accumulated effects of continued operation cause a deterioration in alignment.

In some cases, it is desirable to measure the position of several structures using a single multi-axis interferometer. When this is the case, the number of interferometer axes, and hence the number of components to be aligned, increases. This makes alignment more difficult.

SUMMARY

The invention provides a multi-axis interferometer in which a single monolithic structure includes both the optical elements for forming and directing the beams for each interferometer axis and a multiplexer for dividing a single input beam into beams for each interferometer axis.

In one embodiment, the multi-axis interferometer provides a multi-axis interferometer having an optically transmissive monolith. The monolith has a multiplexer portion and a beam splitter portion. The multiplexer portion is configured to split an input beam into a corresponding plurality of intermediate beams, each of the intermediate beams being directed toward the beam splitter portion through a corresponding output port of the multiplexer portion. The beam splitter portion is configured to separate the intermediate beam into a measurement component and a reference component.

In one embodiment, the multiplexer portion includes a first interior face and a second interior face opposite to the first interior face. An output port is disposed on the second interior face. The output port can include a beam steering element, for example a refractive element for

refracting a beam incident from the first interior face into an intermediate beam normal to the second interior face. In one aspect, the beam steering element is a diffraction grating. However, the beam steering element might also include a volume of material having an index of refraction selected to refract the beam incident from the first interior face into the intermediate beam
5 normal to the second interior face. To form intermediate beams of substantially the same power density, the partially transmissive refractors can have transmissivities selected such that the each of the intermediate beams carries substantially the same power as any other intermediate beam.

The interferometer of the invention can also include a corner reflector in optical communication with the output port and the beam splitter portion. The corner reflector in this
10 embodiment is configured to direct the intermediate beam into the beam splitter portion.

In another embodiment, the multi-axis interferometer includes an optically transparent monolith having a multiplexing layer that divides an input beam into a plurality of intermediate beams and a beam splitting layer that directs a measurement component of each of the intermediate beams along a measurement path, and a reference component of each of the intermediate beams along a reference path. When the reference path includes a target, the path length difference between these two paths provides a basis for measuring distance to an output coupler in optical communication with the multiplexing layer and the beam splitting layer.
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One multiplexing layer includes a first reflector, a second reflector opposite the first reflector; and a beam steering facet oriented to direct the input beam toward the second reflector at a grazing angle. This beam steering facet can be an angled portion of the first reflector.
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The output coupler can include a partially transmissive medium disposed to intercept the input beam. Optionally, the output coupler includes a beam steering element for altering a direction of the intermediate beam. Suitable beam steering elements include a diffraction grating or a region having an appropriately selected refractive index.

25 These and other features of the invention will be apparent from the following detailed description and the accompanying figures, in which:

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is an isometric view of a multi-axis interferometer;

FIG. 2 is a plan view of the measurement face of the interferometer of FIG. 1;

FIG. 3 is a cross-section of the beam multiplexing layer of the interferometer shown in FIG. 1;

FIG. 4 is a cross-section of the feed structure of the interferometer shown in FIG. 1;

FIG. 5 is a cross-section of the interferometer showing the beam-splitting plane;

5 FIG. 6 shows the path followed by the reference component of the intermediate beam in a plane having one retro-reflector;

FIG. 7 shows the path followed by the measurement component of the intermediate beam in a plane having one retro-reflector;

10 FIG. 8 shows the path followed by the reference component of the intermediate beam in a plane having two retro-reflectors; and

FIG. 9 shows the path followed by the measurement component of the intermediate beam in a plane having two retro-reflectors.

DETAILED DESCRIPTION

15 A multi-axis interferometer **10** according to the invention, as shown in FIG. 1, includes an optically transparent monolith **12** having a rear face **14**, a measurement face **16** opposite the rear face **14**, a reference face **18** perpendicular to and connecting the edges of the measurement face **16** and the rear face **14**, and an input/output (“I/O”) face **20** opposite the reference face **18**. With reference to the coordinate system shown in FIG. 1, the measurement and rear faces **16**, **14** are parallel to the *xy* plane; the reference face **18** and the I/O face **20** are parallel to the *yz* plane.

20 The multi-axis interferometer **10** is shown illuminating an edge **22** of a target **24** with an array of measurement beams to detect translation and rotation of the target **24**. With reference to the local *x'y'z*- coordinate system associated with the target **24**, the target **24** is said to experience “pitch” when it rotates about the *x'* axis, “yaw” when it rotates about the *y'* axis, and “roll” when it rotates about the *z'* axis. In the configuration shown, the interferometer **10** cannot detect roll because the distance between the interferometer **10** and the illuminated edge **22** does not change as the target **24** rolls. For similar reasons, the interferometer **10** configured as shown does not detect translation along either the *y'* or the *x'* axis. These motions can be detected by placing a

second interferometer to illuminate a perpendicular edge **26** of the target **24**.

An array of retro-reflectors **28a-g** (designated generally as **28**) is disposed on the rear face **14** of the monolith **12**. In the illustrated embodiment, there are four rows of retro-reflectors, three of which have two columns and one of which has only one column. Each retro-reflector **28** is a corner of a cube having a reflective inner surface. In operation, the array of retro-reflectors **28a-g** forms a corresponding array of measurement beams on the measurement face **16**, as shown in FIG. 2. Each retro-reflector **28** (shown in dashed lines in FIG. 2) is associated with one beam **30** emerging from the portion of the measurement face **16** directly opposite the retro-reflector **28**. Although there appear to be twice as many beams **30** as there are retro-reflectors **28**, this is only an illusion. As will be seen below, the folded path traversed by each beam **30** within the monolith **12** is such that the beam **30** makes two round trips between the monolith **12** and the target **24**.

The configuration of retro-reflectors **28** depends on the constraints of the application. Referring back to FIG. 1, each measurement spot **32a-c** on the target **24** is associated with one retro-reflector **28a-c**. Thus, three retro-reflectors **28a-c** are sufficient to illuminate the three measurement spots **32a-c** that are required to obtain translation, pitch, and yaw of a first target **24**. The illustrated embodiment includes three additional retro-reflectors **28d-f** for providing beams used to measure translation, pitch, and yaw of a second target (not shown). These additional retro-reflectors **28d-f** enable a single interferometer **10** to detect relative motion between the first and second targets. The remaining retro-reflector **28g** and its associated beam is used for measuring surface roughness of the illuminated edge **22**. This information is used to correct the measurement made by the measurement beams associated with the remaining retro-reflectors **28a-f**.

The monolith **12** itself is divided into a multiplexing layer **34** and a beam-splitting layer **36**. As indicated by the dashed line in FIG. 1, these two layers are not joined or affixed to each other. The multiplexing layer **34** and the beam-splitting layer **36** are part of the same monolithic structure in much the same way that the individual transistors of an integrated circuit are part of, or integral with, the same silicon crystal. The multiplexing layer **34** extends from the rear face **14** to the beginning of the beam-splitting layer **36** in the interior of the monolith **12**. This multiplexing layer **34** has opposed first and second mirrored interior faces **36, 38**, best seen in FIG. 3, that are perpendicular to the rear face **14** of the monolith **12**.

5 FIG. 3 shows a cross-section obtained by slicing the multiplexing layer 34 along the xy plane. The first interior face 36 has a first facet 40 that is coplanar with the reference face and a second facet 42 that makes an obtuse angle with the first facet 40. The second interior face 38 is punctuated by a plurality of output couplers 44a-d (designated generally as 44) arranged along a line extending parallel to the rows in the array of retro-reflectors 28. The number of output couplers 44 on the second interior face 38 corresponds to the number of such rows.

10 Referring back to FIG. 1, a feed structure 46, also integral to the monolith 12, protrudes from a bottom edge of the I/O face 20. The feed structure 46 redirects an input laser beam into the multiplexing layer 34, where it is split into a plurality of intermediate beams 50a-d (shown in FIG. 3). Each of the intermediate beams has essentially the same power as all the other intermediate beams.

15 As shown in FIG. 3, the feed structure 46 directs an input beam 48 toward the second facet 42. The second facet 42 reflects the input beam 48 toward a first output coupler 44a along a path that makes a grazing angle relative to a line normal to the second interior face 38. The transmissivity of the first output coupler 44a is selected such that a first quarter of the power in the input beam 48 is transmitted through the first output coupler 44a to form a first intermediate beam 50a. The input beam 48, with its power density diminished by one-quarter, is reflected back toward the first facet 40. Because the input beam 48 is incident on the first facet 40 at a grazing angle, it is reflected by the first facet 40 toward a second output coupler 44b. The transmissivity of the second output coupler 44b is selected such that one third of the power incident thereon is transmitted to form a second intermediate beam 50b. Since the residual power incident on the second output coupler 44b is three-quarters of the original power in the input beam 48, this one third of three-quarters amounts to one-quarter, which is the same amount of power that was transmitted through the first output coupler 44a. As a result, the second intermediate beam 50b has the same power density as the the first intermediate beam 50a. This pattern continues with the third output coupler 44c, which transmits one half of the residual power incident thereon (which amounts to one-quarter of the original power available in the input beam 48), and the fourth and final output coupler 44d, which transmits all the residual power incident thereon. This results in the generation of four intermediate beams 50a-d that ultimately enter the beam-splitting layer 36. While the illustrated example applies to the case of four output couplers 44a-d, the principle shown is applicable to other numbers of output couplers

44.

As shown in FIG. 3, when the input beam **48** is incident on an output coupler **44**, it is incident at a grazing angle relative to the second interior face **38**. This is useful because it allows the reflected portion of the input beam **48** to be reflected back and forth across the multiplexing layer **34** along a zigzag path. It is undesirable, however, for the transmitted portion of the input beam **48** to proceed along this grazing angle as it passes through the output coupler **44**.

The output coupler **44** includes a refractive component for bending the transmitted portion of a beam incident at a grazing angle into an intermediate beam **50** that is normal to the second interior face **38**. In the illustrated embodiment, this is achieved by providing a suitable diffractive element, such as a diffraction grating **52**, as part of the output coupler **44**. Other refractive components can be used however. For example, the refractive component can be a volume of monolith **12** having an appropriate geometry and containing a material having an appropriately selected index of refraction.

In one embodiment, shown in FIG. 4, the feed structure **46** includes a non-polarizing beam splitter **54** that splits the input beam **48** into a first feed beam **56a** and a second feed beam **56b**. This second feed beam **56b** is not shown in FIG. 3 because it is out of the plane of the figure. The first feed beam **56a** will be split into the intermediate beams **50** that illuminate a first column of retro-reflectors. The second feed beam **56b** will be split into the intermediate beams **50** that illuminate a second column of retro-reflectors. The separation between the two columns of retro-reflectors in FIG. 1 (and hence between the second and third columns of beams in FIG. 2) corresponds to the separation between the first and second feed beams **56a, 56b** in FIG. 4. When a feed structure **46** such as that shown in FIG. 4 is in use, the operation of the multiplexing layer **34** is identical to that described above, with the exception that the multiplexing layer **34** operates on the feed beams rather than directly on the input beam **48**.

The beam-splitting layer **36**, shown in the cross section of FIG. 5, is bounded by the I/O face **20**, the reference face **18**, the measurement face **16**, and by the multiplexing layer **34**. A corner reflector **58** is mounted on the I/O face **20** and oriented to direct intermediate beams **50** emerging from the output couplers **44** into the beam-splitting layer **36**. FIG. 5 shows intermediate beams **50** exiting the output coupler **44** in the -x direction and being reflected in the z direction by a rear facet **60** of the corner reflector **58**. A front facet **62** opposite the rear facet

intercepts intermediate beams **50** traveling in the z direction and reflects them in the $+x$ direction, into the beam-splitting layer **36** of the monolith **12**.

The interferometer **10** also includes two quarter-wave retarders. A quarter-wave retarder is an optical element that alters the polarization of light passing through it. When linearly polarized light having a first polarization vector passes through a quarter-wave retarder, it is transformed into circularly polarized light. If this circularly polarized light is reflected back into the quarter-wave plate, (so that it is now circularly polarized in the opposite direction) it is transformed back into linearly polarized light having a second polarization vector orthogonal to the first polarization vector.

A first quarter-wave retarder **64** is mounted between the reference face **18** and a reference mirror **66** disposed outside the monolith **12** on a plane parallel to the reference face **18**. A second quarter-wave retarder **68** is mounted adjacent to the measurement face **16** such that, when a target **24** is positioned for illumination by the interferometer **10**, the second quarter-wave retarder **68** lies between the measurement face **16** and the target **24**.

A beam-splitting plane **70** bisects the beam-splitting layer **36** along a diagonal. The beam-splitting plane **70** is coated with a material that transmits light of one polarization but reflects light of another, orthogonal polarization. In this way, the beam-splitting plane **70** splits a beam having mixed polarization into two linearly polarized beams having orthogonal polarization vectors.

The input beam **48** of the interferometer **10** includes two components: a reference component and a measurement component. Upon entering the beam-splitting layer **36**, the reference component has a first linear polarization (the "P" polarization) and the measurement component has a second linear polarization (the "S" polarization) orthogonal to the P polarization.

FIGS. 6 and 7 show the paths followed by the reference beam and the measurement beam in the plane that intersects the bottom row of retro-reflectors. The measurement beam in these and subsequent figures is shown as a first wavy line; the reference component, which is orthogonally polarized relative to the measurement component, is shown by a second wavy line rotated ninety degrees relative to the first wavy line (and hence appearing to be a straight line).

Although these paths are shown as being displaced from each other, this displacement is shown

only to facilitate understanding the operation of the beam-splitting layer 36. In fact, the measurement and reference components of the beam travel along the same physical path.

In FIG. 6, the reference component of the input beam 48 emerges from the output coupler 44a and reflects twice off the corner reflector 58 before entering the beam-splitting layer 36 through the I/O face 20. The reference component then reaches the beam-splitting plane 70. Since the reference component is P-polarized, it passes through the beam-splitting plane 70, through the reference face 18, and through the first quarter-wave retarder 64 before reflecting off the reference mirror 66. The reference component then crosses the first quarter-wave retarder 64 once more before re-entering the beam-splitting layer 36 through the reference face 18. The first quarter-wave retarder 64 transforms the P-polarized reference component into an S-polarized reference component. As a result, when the reference component again reaches the beam-splitting plane 70, it is reflected into the retro-reflector 28g.

The retro-reflector 28g reverses the reference component's direction so that it again travels toward the beam-splitting plane 70. Since the reference component is still S-polarized, the beam-splitting plane 70 reflects it back out the reference face 18 to the first quarter-wave retarder 64 and finally to the reference mirror 66. The reference mirror 66 then reflects the reference component back toward the first quarter-wave retarder 64. The first quarter-wave retarder 64 transforms the S-polarized reference component into a P-polarized reference component. As a result, when the reference component again reaches the beam-splitting plane 70, it passes through the beam-splitting plane 70 and exits the beam-splitting layer 36 through the I/O face 20.

In FIG. 7, the measurement component of the intermediate beam emerges from the output coupler 44a and reflects twice off the corner reflector 58 before entering the beam-splitting layer 36 through the I/O face 20. The measurement component then reaches the beam-splitting plane 70. Since the measurement component is S-polarized, the beam-splitting plane 70 reflects it toward the measurement face 16. The measurement component then proceeds through the measurement face 16, through the second quarter-wave retarder 68, and on to the target 24. After being reflected from the target 24, the measurement component makes a second pass through the second quarter-wave retarder 68. On this second pass, the second quarter-wave retarder 68 changes the S-polarized measurement component into a P-polarized measurement component. As a result, when the measurement component again reaches the beam-splitting plane 70, it passes straight through and proceeds toward the retro-reflector 28g.

The retro-reflector 28g then reverses the measurement component so that it now travels back toward the measurement face 16. On its way to the measurement face 16, the measurement component again encounters the beam-splitting plane 70. Since the measurement component is still P-polarized at this point, the beam-splitting plane 70 again allows it to pass straight through toward the measurement face 16. The P-polarized measurement component then exits the beam-splitting layer 36 through the measurement face 16, passes through the second quarter-wave retarder 68 and proceeds to the target 24. The target 24 again reflects the measurement component back toward the measurement face 16 and through the second quarter-wave retarder 68.

As mentioned earlier in connection with FIG. 1, the two beams that emerge from the monolith 12 are in reality two parts of the same beam. FIG. 7 now makes it clear why this is so. In fact, the beam that emerges from the monolith 12 in FIG. 1 is only the measurement component of one of the intermediate beams 50 derived from the original input beam 48. The reference component of this intermediate beam cannot be seen in FIG. 1 because, as shown in FIG. 7, the reference component exits the monolith 12 only to reach the reference mirror 66, which cannot be seen in FIG. 1.

On its fourth and final pass through, the second quarter-wave retarder 68 transforms the S-polarized measurement component into a P-polarized measurement component. As a result, when the measurement component again reaches the beam-splitting plane 70, it is reflected toward the I/O face 20 of the beam-splitting layer 36, from which it exits the monolith 12.

It is helpful to keep in mind that the measurement component and the reference component, both in their P and S-polarized states, are traversing the same physical path through the beam-splitting layer 36. The beam that ultimately exits the I/O face 20 is thus made up of an S-polarized reference component and a P-polarized measurement component.

By the time they reach the I/O face 20, both the reference component and the measurement component have traversed a path having an internal portion, in which they were both inside the monolith 12, and an external portion, in which they were both outside the monolith 12. The path lengths for the internal portions are the same for both the measurement component and the reference component. The path lengths for the external portion are, however, different. This difference in path length provides a basis for an interferometric measurement of

the distance to a point on the target 24.

The principles of operation of the beam-splitting layer 36, as illustrated in connection with FIGS. 6 and 7, are readily extended to the case in which there are two or more retro-reflectors. FIGS. 8 and 9 show the paths traversed by two reference components (FIG. 8) and two measurement components (FIG. 9) in a cross-section of the interferometer 10 that lies in a plane intersecting two retro-reflectors 28a-b. One reference component in FIG. 8 and a measurement component in the corresponding location in FIG. 9 are associated with a first intermediate beam, which was derived from the first feed beam 56a shown in FIG. 4. The other reference component in FIG. 8 and the remaining measurement component in FIG. 9 are associated with the second intermediate beam, which was derived from the second feed beam 56b shown in FIG. 4. The paths taken by each reference component and each measurement component are similar to those already described in connection with FIGS. 6 and 7, and need not be discussed in detail.

FIGS. 8 and 9 also illustrate how the two feed beams shown in FIG. 4 illuminate different retro-reflectors in the same row. The reference and measurement components of the first intermediate beam illuminate the first retro-reflector. Similarly, the reference component and measurement components of the the second intermediate beam illuminate the second retro-reflector. Additional retro-reflectors can be fed by providing additional feed beams for generating additional intermediate beams. This can be achieved by providing additional beam splitters in the feed structure 46 shown in FIG. 4.

Having described all the components of the interferometer 10, it is now possible to summarize the operation of the multi-axis interferometer 10 as follows. First, an input beam 48 enters the monolith 12 at the feed structure 46. This input beam 48 includes a reference component and a measurement component that are distinguishable by their respective polarizations. The feed structure 46 divides the input beam 48 into two feed beams 56a-b.

The first feed beam 56a climbs the multiplexing layer 34 of the monolith 12 in a zigzag path having as many switchbacks as there are rows of retro-reflectors. At the end of each switchback, a component of the first feed beam 56a exits the multiplexing layer 34 through an output coupler 44. This portion becomes an intermediate beam that can be used to illuminate a retro-reflector in the row of retro-reflectors that is coplanar with that output coupler 44. In this

way, the first feed beam **56a** generates as many intermediate beams as there are switchbacks on the zigzag path.

Meanwhile, the second feed beam **56b** also climbs the multiplexing layer **34** along an identical zigzag path that is displaced from the zigzag path traversed by the first feed beam **56a**.
5 At the end of each switchback, a portion of the second feed beam **56b** also exits the multiplexing layer **34** through an output coupler **44**. This results in the formation of another intermediate beam that can be used to illuminate another retro-reflector in the row of retro-reflectors that is coplanar with that output coupler **44**. In this way, the second feed beam **56b**, like the first feed beam **56a**, generates as many intermediate beams as there are switchbacks on the zigzag path.

10 In addition to allowing a portion of each feed beam to escape the multiplexing layer **34**, each output coupler **44** also corrects the direction of the intermediate beam that emerges. This is achieved by providing a refractive element that refracts the intermediate beam into a direction normal to the output coupler **44**.

15 Once the intermediate beams exit the multiplexing layer **34**, they pass into the corner reflector **58**. The corner reflector **58** redirects the intermediate beams back into the monolith **12**, and in particular, into the beam-splitting layer **36** of the monolith **12**. The beam-splitting layer **36** sends the measurement component of each intermediate beam toward the target **24** and the reference component of each intermediate beam toward the reference plane. It can do so because the reference component and the measurement component of each intermediate beam enter the beam-splitting layer **36** with different polarizations. As a result, the measurement and reference components can be selectively redirected by optical surfaces that transmit selected polarizations and reflect all other polarizations.
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25 By the time they exit the beam splitting layer **36**, the reference component and the measurement component will have traversed different distances. This difference can be used as a basis for an interferometric measurement.

Having described the invention and a preferred embodiment thereof, what I claim as new, and secured by letters patent is: